

AN OPTICAL SIGNAL MULTIPLEXER/DEMULITPLEXER EMPLOYING PSEUDORANDOM MODE MODULATION

BACKGROUND OF THE INVENTION

5

Field of the Invention:

This invention relates generally to optical signal processing and more particularly to an optical multiplexing apparatus employing pseudorandom bit sequence (PRBS) mode 10 modulation.

Description of the Related Art

Optical networks using wavelength-division-multiplexing (WDM) and Dense 15 WDM (DWDM) techniques have been installed throughout the world in response to increasing demand for communications channel capacity. Recent advances in WDM and DWDM technology have focused on improving capacity with either smaller channel wavelength spacing or wider wavelength range. Channel spacing is limited by many factors, including optical filter efficacy, frequency drift, interferometric crosstalk, fiber 20 dispersion and nonlinearity. The art is replete with various multiplexing proposals for obtaining additional capacity in existing optical fiber systems.

Some early practitioners proposed exploiting available WDM bandwidth by using 25 a polarization-division-multiplexing (PDM) scheme in which independent WDM channel signals are simultaneously transmitted on orthogonal polarizations to reduce interchannel crosstalk and improve the operation of optical filtering of adjacent channels. For example, Hill *et al.* ("Optical Polarization Division Multiplexing at 4 Gb/s." *IEEE Photon. Technol. Lett.*, Vol. 4, No. 5, pp. 500-502, May 1992) proposes challenging the speed bottleneck in the electronic circuit components used for time-division multiplexing operations by 30 using a simple PDM system for doubling channel capacity by simultaneously transmitting

two independent data sets as two optical signals having separate optical states of polarization (SOPs). Hill *et al.* distinguish PDM from the polarization shift keying (POLSK) technique used to transmit the bits from a single-word generator in any of two or more polarization states. The Hill *et al.* system uses simple coherent heterodyne 5 detection to demultiplex the two signals and is admittedly impractical without additional (unspecified) polarization control techniques to compensate for the effects of PMD in fibers longer than a few thousand meters.

Generally, there is now an accepted understanding in the art that simple PDM in 10 optical fibers longer than a few thousand meters is practical only for soliton (a solitary wave with nearly lossless propagation) trains because of polarization mode dispersion (PMD). In an early paper, Evangelides *et al.* ("Polarization Multiplexing with Solitons," *IEEE J. Lightwave Technol.*, Vol. 10, No. 1, pp. 28-35, Jan 1992) showed that solitons launched into a fiber with orthogonal polarization may be demultiplexed at the output (so 15 long as crosstalk is avoided by ensuring the solitons do not overlap in time) because the common transit history of the solitons imposes identical polarization errors on each, thereby ensuring that the relative polarization orthogonality is undisturbed by any amount of PDM encountered in the fiber, even over distances of thousands of kilometers. Evangelides *et al.* note that the polarization channel separation possible with solitons is not 20 possible with other pulses. Later, Ono *et al.* ("Polarization Control Method for Suppressing Polarization Mode Dispersion Influence in Optical Transmission Systems," *IEEE J. Lightwave Technol.*, Vol. 12, No. 5, pp. 891-8, May 1994)

Indeed, because the combination of polarization-dependent loss (PDL), 25 polarization dependent gain (PDG) and PMD all contribute to fading in WDM systems, most existing WDM systems employ polarization scrambling to minimize unwanted fading, thereby teaching against any use of PDM for increased channel capacity. For example, in U.S. Patent No. 6,137,925, Stimple *et al.* disclose a multi-wavelength polarization scrambling device intended to minimize the correlation of signal polarization in a WDM 30 channel.

Nevertheless, some practitioners proposed using PDM with soliton trains to overcome specific problems unrelated to optical fiber channel capacity. For instance, in U.S. Patent No. 6,188,768 B1, Bethune *et al.* disclose an autocompensating quantum cryptographic key distribution system based on using soliton trains with PDM to ensure the impossibility of accurate eavesdropping. Others propose using PDM in free-space optical communications systems not subject to significant PMD. For example, Kuri *et al.* (“Multiple Polarization Modulation (MPLM) System for Coherent Optical Space Communication,” *Global Telecommunications Conference, 1995. GLOBECOM '95.*, IEEE, Vol. 3, pp. 2003-2007, 1995) proposes a novel MPLM system for the simultaneous independent transmission of modulated subcarriers and baseband signals. Kuri *et al.* individually modulate the polarization ellipticity angle and the polarization azimuth angle with the modulated subcarriers and baseband signals, respectively, to avoid phase noise and polarization axis mismatch at the receiver.

Recently, some practitioners have proposed using sophisticated variations of the basic PDM concept to improve particular features of optical fiber channel performance. For example, in U.S. Patent No. 5,900,957, Van Der Tol discloses an optical packet switching system that encodes the data and address information in two orthogonally-polarized signals that may be easily separated using passive optical devices. Van Der Tol observes that glass fibers usually do not maintain polarization over kilometer distances and therefore suggest several features intended to protect the relative orthogonality of the two polarized signals over long distances, a feature reminiscent of the earlier soliton train PDM systems. In another example, Hayee *et al.* (Summaries of Papers Presented at the *Conference on Lasers and Electro-Optics, 1999. CLEO '99.* pp. 181-182, 1999) describe a method for multiplexing two orthogonal polarizations of the same wavelength in a power ratio of two-to-one to partially overcome the well-known impracticality of PDM over kilometer distances because of random variations in fiber birefringence. By decorrelating the two signals in time, unbalancing them in power, and operating the modulators only in binary mode to exploit its full extinction ratio, Hayee *et al.* manage to squeeze enough improvement out of the PDM technique to demonstrate useful performance over a 95-km fiber. In yet another example, Zheng *et al.* (“Suppression of Interferometric Crosstalk and

ASE Noise Using a Polarization Multiplexing Technique and a SOA," *IEEE Photon. Technol. Lett.*, Vol. 12, No. 8, pp. 1091-1093, Aug 2000) propose a PDM technique for overcoming amplified spontaneous emission (ASE) noise from optical amplifiers and crosstalk at the signal wavelength. Using a semiconductor optical amplifier (SOA), Zheng *et al.* multiplex an optical signal and its inverse as two orthogonally-polarized signals, the amplitudes of which add to a fixed value of logical one. Transmitting the two signals from the same SOA results in a fixed saturated output power level that solves the ASE and interference problems (both are significantly suppressed by the saturated SOA). The original signal is demultiplexed at the receiver with a polarization beam splitter (PBS) but 5 Zheng *et al.* do not consider operation over fibers longer than 45 km. Similarly, Srivastava *et al.* ("A Polarization Multiplexing Technique to Mitigate WDM Crosstalk in SOAs," *IEEE Photon. Technol. Lett.*, Vol. 12, No. 10, pp. 1415-6, Oct 2000) suggests using polarization multiplexing to overcoming the effects of the crosstalk arising from 10 SOA gain saturation. Two orthogonally-polarized optical signals are modulated with the data stream and its complement before being combined to form a signal having a constant average power without bit transition patterns. The two wavelength channels are then 15 decorrelated by sending through a 10-km single-mode fiber to introduce a delay between the two channels. They report an additional 1 dB bit error rate (BER) power penalty because of the accumulated dispersion through the decorrelation and transmission fiber 20 sections but do not discuss PMD or polarization dispersion loss (PDL).

As may be readily appreciated from these examples, there is a clearly-felt need in the art for a modulation method that improves the capacity of an optical channel subject to random fluctuations in fiber birefringence over long distances. These unresolved 25 problems and deficiencies are clearly felt in the art and are solved by this invention in the manner described below.

SUMMARY OF THE INVENTION

This invention solves the above-cited problem by providing for the first time an 30 optical signal multiplexer/demultiplexer employing an orthogonal pseudorandom (PRN)

coding scheme for optical mode modulation to produce a plurality of independent optical signals that may be combined into one multiplex signal for transmission over an optical fiber to the receiving end, where the multiplex signal may be demultiplexed by relying on the orthogonal properties of the PRN code to isolate each independent optical signal from
5 the transmitted multiplex signal. In channels subject to mode modulation distortion, one of the signal components may be used as a pilot signal to obtain a correction for channel mode modulation distortion. The PRN optical signal multiplexer/demultiplexer is particularly useful with polarization mode modulation.

10 It is a purpose of this invention to provide a mode modulation method that permits transmission of a plurality of independent optical signals through an optical channel. It is a feature of the method of this invention that a plurality of independent optical signals may be multiplexed and transmitted through free space or an optical waveguide and recovered at the receiving end by demultiplexing.

15 In one aspect, the invention is a method for transmitting a plurality (I) of independent optical signals $\{S_i\}$ through an optical channel having two ends, including the steps of generating a plurality (I) of independent pseudorandom bit sequences (PRBSs), modulating a preselected optical mode of the i^{th} independent optical signal S_i according to the i^{th} independent pseudorandom bit sequence PRBS_i to form an i^{th} modulated optical signal MS_i, where $i = \{1, \dots, I\}$, combining a plurality (I) of the modulated optical signals $\{MS_i\}$ to form an optical multiplex signal, transmitting the optical multiplex signal through the optical channel from one end to the other end, modulating the preselected optical mode of the optical multiplex signal according to the i^{th} pseudorandom bit sequence PRBS_i to form an i^{th} modulated multiplex signal MMS_i, and passing the i^{th} modulated multiplex signal MMS_i through a mode filter, whereby the independent optical signal S_i is recovered.
20
25

30 In an exemplary embodiment, the invention is an apparatus for transmitting a plurality (I) of independent optical signals $\{S_i\}$ in an optical channel, including a first pseudorandom bit sequence (PRBS) generator for generating a plurality (I) of independent PRBSs, a plurality (I) of electro-optical modulators each coupled to the PRBS generator

and disposed to modulate the polarization mode of the i^{th} optical signal S_i according to the i^{th} pseudorandom bit sequence PRBS_i to form a modulated optical signal MS_i, where $i = \{1, \dots, I\}$, an optical combiner disposed at one end of the optical channel for combining a plurality (I) of the modulated optical signals {MS_i} to form an optical 5 multiplex signal, optical channel input means coupled to the optical combiner for accepting the optical multiplex signal for transmission through the optical channel, at least one electro-optical modulator coupled to the PRBS generator and disposed at the other end of the optical channel for modulating the polarization mode of the optical multiplex signal according to the i^{th} pseudorandom bit sequence PRBS_i to form an i^{th} modulated multiplex 10 signal MMS_i, and a polarized filter disposed at the other end of the optical channel to filter the i^{th} modulated multiplex signal MMS_i, whereby the independent optical signal S_i is recovered.

15 The foregoing, together with other objects, features and advantages of this invention, can be better appreciated with reference to the following specification, claims and the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWINGS

20 For a more complete understanding of this invention, reference is now made to the following detailed description of the embodiments as illustrated in the accompanying drawing, in which like reference designations represent like features throughout the several views and wherein:

25 Fig. 1 is a schematic diagram illustrating the system of this invention for transmitting a plurality (I) of independent optical signals {S_i} through a single optical channel;

30 Figs. 2A-B are schematic diagrams illustrating the system of this intention for transmitting a polarization mode distortion (PMD) pilot signal through a single optical channel;

Fig. 3 is a block diagram illustrating an exemplary embodiment of the apparatus of this invention for transmitting a plurality (I) of independent optical signals $\{S_i\}$ through a single optical channel; and

5 Fig. 4 is a schematic diagram of a flowchart illustrating the method of this invention for transmitting a plurality (I) of independent optical signals $\{S_i\}$ through a single optical channel.

DESCRIPTION OF THE PREFERRED EMBODIMENT

10 In a pseudorandom (PRN) coding scheme, the signal energy is spread over some signal parameter, such as phase or frequency, according to one of a set of data sequences that are statistically orthogonal. In the system of this invention, the signal energy is spread in an optical mode, such as polarization, before transmission over a common optical channel. Thus, several independent optical signals may each be spread in mode and combined for transmission over a single channel, as may be appreciated with reference to 15 Fig. 1.

20 Fig. 1 is a schematic diagram illustrating the system 10 of this invention for transmitting a plurality (I) of independent optical signals $\{S_i\}$ through a single optical channel. Three independent optical signals S_1 , S_2 and S_3 , each of which may be amplitude-modulated and of identical frequency and phase, for example, are shown coupled to separate mode modulators, which may include, for example, electro-optical polarizers. The three mutually orthogonal PRN sequences P_1 , P_2 and P_3 each have a white or Gaussian 25 spectral density function and may include a Gold code, Walsh code, or any other suitable digital sequence having the necessary orthogonality and white spectral characteristics. The mode modulator 12 accepts a PRN sequence P_1 and varies the polarization mode of signal S_1 to produce the modulated optical signal 14. Similarly, the mode modulator 16 accepts a PRN sequence P_2 and varies the polarization mode of signal S_2 to produce the modulated 30 optical signal 18 and the mode modulator 20 accepts a PRN sequence P_3 and varies the

polarization mode of signal S_3 to produce the modulated optical signal 22. This example includes only three signals but may be scaled to larger numbers of signals.

Modulated optical signals 14, 18, and 22 are accepted at the optical combiner 24 wherein they are combined to form a single optical multiplex signal that is coupled to one end 26 of the optical channel 28. The other end 30 of optical channel 28 is coupled to an optical splitter 32, which splits the single optical multiplex signal into the three optical multiplex signal copies 34, 36 and 38. Optical multiplex signal 34 is coupled to the mode demodulator 40, which may include, for example, an electro-optical polarizer and a polarization filter. Similarly, optical multiplex signal 36 is coupled to the mode demodulator 42 and optical multiplex signal 38 is coupled to the mode demodulator 44.

The operation of mode modulators 40, 42 and 44 are very similar and may be appreciated from the description of mode modulator 40. PRN sequences P_1 , P_2 and P_3 are reproduced at the receiving end 30 of optical channel 28 by any useful method known in the art. For example, a second PRN generator may be employed with the same algorithms and seed values to produce the PRN sequences P_1 , P_2 and P_3 in synchronization with the PRN generator employed to produce the PRN sequences P_1 , P_2 and P_3 used at the end 26 of optical channel 28. As another example, synchronization data bits may be transferred as an additional signal S_4 (not shown) through optical channel 28. PRN sequence P_1 is coupled to mode demodulator 40, which modulates the polarization mode of optical multiplex signal 34 accordingly to produce an intermediate modulated multiplex signal MMS_1 (not shown). Intermediate modulated multiplex signal MMS_1 is then filtered to remove all optical signal power having a polarization mode that is uncorrelated with PRN sequence P_1 , leaving the recovered signal $R_1 = S_1$.

In channels with polarization mode modulation distortion (PMD), which is generally slowly varying or invariant, one of the optical signals may be used as a PMD pilot signal S_p to obtain a correction for channel PMD by introducing a variable delay between the quadrature components of the pilot signal S_p and varying the delay as necessary to properly recover the pilot signal S_p . For example, a single-mode fiber from

a splitter can be rotated physically to orthogonalize the signal polarization between the splitter outputs and the components then combined and transmitted as a pilot signal S_p with a known relative polarization. By splitting the two orthogonal pilot signal components at the receiver and varying the time delay between them, a correction for
5 mode dispersion may be determined and used to correct other contemporaneous signals subjected to the same mode dispersion in the common optical channel. Figs. 2A-B are schematic diagrams illustrating the system of this invention for transmitting a PMD pilot signal S_p through a single optical channel. Fig. 2A shows the transmit end apparatus 46 and Fig. 2B shows the receive end apparatus 48 for the PMD pilot signal S_p .

10

In Fig. 2A, a laser 50 creates an optical signal 52, which is passed through a half-wave plate 54 to fix its polarization mode and a beam-splitter 56 to generate two identical optical signals 56 and 58 having a known state of polarization (SOP). A pilot signal bit sequence 60 is applied to the two identical mode modulators 62 and 64 to create two identical modulated pilot signals 66 and 68, which are coupled via polarization-maintaining fibers to the respective arms of the polarization combiner 70. Each arm of polarization combiner 70 properly couples only through one SOP, which is acquired by appropriately rotating the polarization-maintaining optical fibers carrying signals 66 and 68 with respect to the respective fibers in polarization-combiner 70. Thus, polarization combiner 70 adds 15 two orthogonally-polarized pilot signals 66 and 68 to produce a dual-SOP pilot signal 72, which is transmitted through the optical channel 74.

20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
425
430
435
440
445
450
455
460
465
470
475
480
485
490
495
500
505
510
515
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
605
610
615
620
625
630
635
640
645
650
655
660
665
670
675
680
685
690
695
700
705
710
715
720
725
730
735
740
745
750
755
760
765
770
775
780
785
790
795
800
805
810
815
820
825
830
835
840
845
850
855
860
865
870
875
880
885
890
895
900
905
910
915
920
925
930
935
940
945
950
955
960
965
970
975
980
985
990
995
1000
1005
1010
1015
1020
1025
1030
1035
1040
1045
1050
1055
1060
1065
1070
1075
1080
1085
1090
1095
1100
1105
1110
1115
1120
1125
1130
1135
1140
1145
1150
1155
1160
1165
1170
1175
1180
1185
1190
1195
1200
1205
1210
1215
1220
1225
1230
1235
1240
1245
1250
1255
1260
1265
1270
1275
1280
1285
1290
1295
1300
1305
1310
1315
1320
1325
1330
1335
1340
1345
1350
1355
1360
1365
1370
1375
1380
1385
1390
1395
1400
1405
1410
1415
1420
1425
1430
1435
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
1495
1500
1505
1510
1515
1520
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
1630
1635
1640
1645
1650
1655
1660
1665
1670
1675
1680
1685
1690
1695
1700
1705
1710
1715
1720
1725
1730
1735
1740
1745
1750
1755
1760
1765
1770
1775
1780
1785
1790
1795
1800
1805
1810
1815
1820
1825
1830
1835
1840
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
2110
2115
2120
2125
2130
2135
2140
2145
2150
2155
2160
2165
2170
2175
2180
2185
2190
2195
2200
2205
2210
2215
2220
2225
2230
2235
2240
2245
2250
2255
2260
2265
2270
2275
2280
2285
2290
2295
2300
2305
2310
2315
2320
2325
2330
2335
2340
2345
2350
2355
2360
2365
2370
2375
2380
2385
2390
2395
2400
2405
2410
2415
2420
2425
2430
2435
2440
2445
2450
2455
2460
2465
2470
2475
2480
2485
2490
2495
2500
2505
2510
2515
2520
2525
2530
2535
2540
2545
2550
2555
2560
2565
2570
2575
2580
2585
2590
2595
2600
2605
2610
2615
2620
2625
2630
2635
2640
2645
2650
2655
2660
2665
2670
2675
2680
2685
2690
2695
2700
2705
2710
2715
2720
2725
2730
2735
2740
2745
2750
2755
2760
2765
2770
2775
2780
2785
2790
2795
2800
2805
2810
2815
2820
2825
2830
2835
2840
2845
2850
2855
2860
2865
2870
2875
2880
2885
2890
2895
2900
2905
2910
2915
2920
2925
2930
2935
2940
2945
2950
2955
2960
2965
2970
2975
2980
2985
2990
2995
3000
3005
3010
3015
3020
3025
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
3095
3100
3105
3110
3115
3120
3125
3130
3135
3140
3145
3150
3155
3160
3165
3170
3175
3180
3185
3190
3195
3200
3205
3210
3215
3220
3225
3230
3235
3240
3245
3250
3255
3260
3265
3270
3275
3280
3285
3290
3295
3300
3305
3310
3315
3320
3325
3330
3335
3340
3345
3350
3355
3360
3365
3370
3375
3380
3385
3390
3395
3400
3405
3410
3415
3420
3425
3430
3435
3440
3445
3450
3455
3460
3465
3470
3475
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
3540
3545
3550
3555
3560
3565
3570
3575
3580
3585
3590
3595
3600
3605
3610
3615
3620
3625
3630
3635
3640
3645
3650
3655
3660
3665
3670
3675
3680
3685
3690
3695
3700
3705
3710
3715
3720
3725
3730
3735
3740
3745
3750
3755
3760
3765
3770
3775
3780
3785
3790
3795
3800
3805
3810
3815
3820
3825
3830
3835
3840
3845
3850
3855
3860
3865
3870
3875
3880
3885
3890
3895
3900
3905
3910
3915
3920
3925
3930
3935
3940
3945
3950
3955
3960
3965
3970
3975
3980
3985
3990
3995
4000
4005
4010
4015
4020
4025
4030
4035
4040
4045
4050
4055
4060
4065
4070
4075
4080
4085
4090
4095
4100
4105
4110
4115
4120
4125
4130
4135
4140
4145
4150
4155
4160
4165
4170
4175
4180
4185
4190
4195
4200
4205
4210
4215
4220
4225
4230
4235
4240
4245
4250
4255
4260
4265
4270
4275
4280
4285
4290
4295
4300
4305
4310
4315
4320
4325
4330
4335
4340
4345
4350
4355
4360
4365
4370
4375
4380
4385
4390
4395
4400
4405
4410
4415
4420
4425
4430
4435
4440
4445
4450
4455
4460
4465
4470
4475
4480
4485
4490
4495
4500
4505
4510
4515
4520
4525
4530
4535
4540
4545
4550
4555
4560
4565
4570
4575
4580
4585
4590
4595
4600
4605
4610
4615
4620
4625
4630
4635
4640
4645
4650
4655
4660
4665
4670
4675
4680
4685
4690
4695
4700
4705
4710
4715
4720
4725
4730
4735
4740
4745
4750
4755
4760
4765
4770
4775
4780
4785
4790
4795
4800
4805
4810
4815
4820
4825
4830
4835
4840
4845
4850
4855
4860
4865
4870
4875
4880
4885
4890
4895
4900
4905
4910
4915
4920
4925
4930
4935
4940
4945
4950
4955
4960
4965
4970
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
5030
5035
5040
5045
5050
5055
5060
5065
5070
5075
5080
5085
5090
5095
5100
5105
5110
5115
5120
5125
5130
5135
5140
5145
5150
5155
5160
5165
5170
5175
5180
5185
5190
5195
5200
5205
5210
5215
5220
5225
5230
5235
5240
5245
5250
5255
5260
5265
5270
5275
5280
5285
5290
5295
5300
5305
5310
5315
5320
5325
5330
5335
5340
5345
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
5400
5405
5410
5415
5420
5425
5430
5435
5440
5445
5450
5455
5460
5465
5470
5475
5480
5485
5490
5495
5500
5505
5510
5515
5520
5525
5530
5535
5540
5545
5550
5555
5560
5565
5570
5575
5580
5585
5590
5595
5600
5605
5610
5615
5620
5625
5630
5635
5640
5645
5650
5655
5660
5665
5670
5675
5680
5685
5690
5695
5700
5705
5710
5715
5720
5725
5730
5735
5740
5745
5750
5755
5760
5765
5770
5775
5780
5785
5790
5795
5800
5805
5810
5815
5820
5825
5830
5835
5840
5845
5850
5855
5860
5865
5870
5875
5880
5885
5890
5895
5900
5905
5910
5915
5920
5925
5930
5935
5940
5945
5950
5955
5960
5965
5970
5975
5980
5985
5990
5995
6000
6005
6010
6015
6020
6025
6030
6035
6040
6045
6050
6055
6060
6065
6070
6075
6080
6085
6090
6095
6100
6105
6110
6115
6120
6125
6130
6135
6140
6145
6150
6155
6160
6165
6170
6175
6180
6185
6190
6195
6200
6205
6210
6215
6220
6225
6230
6235
6240
6245
6250
6255
6260
6265
6270
6275
6280
6285
6290
6295
6300
6305
6310
6315
6320
6325
6330
6335
6340
6345
6350
6355
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
6430
6435
6440
6445
6450
6455
6460
6465
6470
6475
6480
6485
6490
6495
6500
6505
6510
6515
6520
6525
6530
6535
6540
6545
6550
6555
6560
6565
6570
6575
6580
6585
6590
6595
6600
6605
6610
6615
6620
6625
6630
6635
6640
6645
6650
6655
6660
6665
6670
6675
6680
6685
6690
6695
6700
6705
6710
6715
6720
6725
6730
6735
6740
6745
6750
6755
6760
6765
6770
6775
6780
6785
6790
6795
6800
6805
6810
6815
6820
6825
6830
6835
6840
6845
6850
6855
6860
6865
6870
6875
6880
6885
6890
6895
6900
6905
6910
6915
6920
6925
6930
6935
6940
6945
6950
6955
6960
6965
6970
6975
6980
6985
6990
6995
7000
7005
7010
7015
7020
7025
7030
7035
7040
7045
7050
7055
7060
7065
7070
7075
7080
7085
7090
7095
7100
7105
7110
7115
7120
7125
7130
7135
7140
7145
7150
7155
7160
7165
7170
7175
7180
7185
7190
7195
7200
7205
7210
7215
7220
7225
7230
7235
7240
7245
7250
7255
7260
7265
7270
7275
7280
7285
7290
7295
7300
7305
7310
7315
7320
7325
7330
7335
7340
7345
7350
7355
7360
7365
7370
7375
7380
7385
7390
7395
7400
7405
7410
7415
7420
7425
7430
7435
7440
7445
7450
7455
7460
7465
7470
7475
7480
7485
7490
7495
7500
7505
7510
7515
7520
7525
7530
7535
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
7605
7610
7615
7620
7625
7630
7635
7640
7645
7650
7655
7660
7665
7670
7675
7680
7685
7690
7695
7700
7705
7710
7715
7720
7725
7730
7735
7740
7745
7750
7755
7760
7765
7770
7775
7780
7785
7790
7795
7800
7805
7810
7815
7820
7825
7830
7835
7840
7845
7850
7855
7860
7865
7870
7875
7880
7885
7890
7895
7900
7905
7910
7915
7920
7925
7930
7935
7940
7945
7950
7955
7960
7965
7970
7975
7980
7985
7990
7995
8000
8005
8010
8015
8020
8025
8030
8035
8040
8045
8050
8055
8060
8065
8070
8075
8080
8085
8090
8095
8100
8105
8110
8115
8120
8125
8130
8135
8140
8145
8150
8155
8160
8165
8170
8175
8180
8185
8190
8195
8200
8205
8210
8215
8220
8225
8230
8235
8240
8245
8250
8255
8260
8265
8270
8275
8280
8285
8290
8295
8300
8305
8310
8315
8320
8325
8330
8335
8340
8345
8350
8355
8360
8365
8370
8375
8380
8385
8390
8395
8400
8405
8410
8415
8420
8425
8430
8435
8440
8445
8450
8455
8460
8465
8470
8475
8480
8485
8490
8495
8500
8505
8510
8515
8520
8525
8530
8535
8540
8545
8550
8555
8560
8565
8570
8575
8580
8585
8590
8595
8600
8605
8610
8615
8620
8625
8630
8635
8640
8645
8650
8655
8660
8665
8670
8675
8680
8685
8690
8695
8700
8705
8710
8715
8720
8725
8730
8735
8740
8745
8750
8755
8760
8765
8770
8775
8780
8785
8790
8795
8800
8805
8810
8815
8820
8825
8830
8835
8840
8845
8850
8855
8860
8865
8870
8875
8880
8885
8890
8895
8900
8905
8910
8915
8920
8925
8930
8935
8940
8945
8950
8955
8960
8965
8970
8975
8980
8985
8990
8995
9000
9005
9010
9015
9020
9025
9030
9035
9040
9045
9050
9055
9060
9065
9070
9075
9080
9085
9090
9095
9100
9105
9110
9115
9120
9125
9130
9135
9140
9145
9150
9155
9160
9165
9170
9175
9180
9185
9190
9195
9200
9205
9210
9215
9220
9225
9230
9235
9240
9245
9250

compensation signal 94, which may be used to correct for the slowly varying mode distortion in channel 74.

Fig. 3 is a block diagram illustrating an exemplary embodiment of the apparatus 5 96 of this invention for transmitting a plurality (I) of independent optical signals $\{S_i\}$ through a single optical channel 98, which may include free space or an optical waveguide or the like. A pseudorandom bit sequence (PRBS) generator 100 provides a set of code sequences $\{P_i\}$ that have the mutually orthogonal and white spectral properties known in the signal processing arts for code division multiplexing. Thus, as is well-known for such 10 code sequences, P_i is uncorrelated with P_j if $i \neq j$ and P_i has a white spectral density and is unlikely to introduce any ambiguities when added to another signal. A plurality of electro-optical modulators exemplified by the electro-optical modulator 102 are each disposed to accept one signal S_i of a plurality of independent optical signals $\{S_i\}$, which may be, for example, an amplitude-modulated laser output signal carrying data that is to 15 be transmitted through optical channel 98. Electro-optical modulator 102 accepts the optical signal S_1 and modulates the polarization mode of S_1 according to the PRBS P_1 to produce the modulated optical signal MS_1 . The other electro-optical modulators operate similarly and together produce the plurality of modulated optical signals $\{MS_i\}$, which are coupled to the optical combiner 104. Optical combiner 104 merely adds the plurality of 20 modulated optical signals $\{MS_i\}$ to form a single optical multiplex signal 106, which is coupled to the optical channel input 108.

After propagating through optical channel 98, an optical multiplex signal 110, 25 representing a version of optical multiplex signal 106 with some degree of additional noise and distortion, is coupled by way of the optical channel output 112 to an optical splitter 114, which creates a plurality of identical copies of optical multiplex signals 110. Another plurality of electro-optical modulators, exemplified by the electro-optical modulator 116, are each disposed to accept one copy of optical multiplex signals 110. A second PRBS generator 118 provides the set of code sequences $\{P_i\}$ and is synchronized with PRBS generator 100 by any useful means known in the art, such as a synchronous clock recovery scheme or an additional PRBS correlator 120 disposed to ensure accurate duplication and 30

5 synchrony of the PRBSs 100 and 118 at each end of optical channel 98. Electro-optical modulator 116 accepts optical multiplex signal 110 and modulates the polarization mode thereof according to P_1 to produce the modulated multiplex signal MMS₁ in which all of the energy correlated with P_1 is now propagating in a single SOP. Modulated multiplex signal MMS₁ is then filtered by a polarized mode filter 122 to remove all signal energy except the energy having the SOP for which mode filter 122 is tuned. Because of the fixed SOP, mode filter 122 passes only the energy in MMS₁ that is correlated to P_1 . This includes only the original S₁ because all other energy is uncorrelated by virtue of the orthogonality of the set of PRBSs {P_i}. The other electro-optical modulators operate similarly 10 and together produce the plurality of modulated multiplex signals {MMS_i}, each of which is then filtered by a mode filter tuned to a single SOP, thereby recovering the plurality (I) of independent optical signals {S_i}. If desired, the SOP of the mode filters, exemplified by mode filter 122, may be dynamically adjusted to compensate for PMD in optical channel 98 by some means such described above in connection with Figs. 2A-2B.

15

Fig. 4 is a schematic diagram of a flowchart illustrating the method of this invention for transmitting a plurality (I) of independent optical signals {S_i} through a single optical channel. In the first step 124, the plurality (I) of PRBSs {P_i} is generated and, in step 126, the plurality (I) of independent optical signals {S_i} is produced. In the next step 128, a preselected optical mode, such as the SOP, of the independent optical signal S_i is modulated with the ith PRBS P_i to form an ith modulated optical signal MS_i, for i = {1, . . . I}. In the step 132, the plurality (I) of modulated optical signals {MS_i} is combined 20 into an optical multiplex signal, which is transmitted through the optical channel from one end to the other in the step 132. In step 134, the preselected optical mode of the received optical multiplex signal is modulated with the ith PRBS P_i to form an ith modulated multiplex signal MMS_i. Finally, in the last step 136, the ith modulated multiplex signal MMS_i is filtered with a mode filter to remove uncorrelated energy and recover the independent optical signal S_i. Each of these steps may be repeated for i = {1, . . . I} if appropriate.

25
30

Clearly, other embodiments and modifications of this invention may occur readily to those of ordinary skill in the art in view of these teachings. Therefore, this invention is to be limited only by the following claims, which include all such embodiments and modifications when viewed in conjunction with the above specification and accompanying drawing.

WE CLAIM: